IAC –05 –C1.7.01

LAUNCH WINDOW ANALYSIS FOR KALPANA-1

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ABSTRACT

The KALPANA-1 spacecraft is providing continuity of meteorological services from the INSAT system in the Indian region. It was the first payload to be launched by ISRO's Polar Satellite Launch Vehicle (PSLV) from the Satish Dhawan Space Center, Sriharikota (SHAR), with a lift-off mass of 1055 kg, into a Geostationary Transfer Orbit (GTO). The s/c carries a 3 channel very high resolution radiometer and a weather data relay transponder. This paper describes the launch window analysis for KALPANA-1. KALPANA-1 is equipped with two earth sensors, each with two detectors mounted at +/- 6.1 deg from Yaw axis in the Pitch-Yaw plane. The earth sensors (ES) provide roll and pitch data. There are three gyroscopes, mounted along each of the body axes. There is a digital sun sensor (DSS), mounted along the roll axis, which provides pitch and yaw information. The liquid apogee motor (LAM) firing is carried out with the gyros as attitude reference. The gyros are calibrated prior to the LAM firing using ES and DSS data. A method, the details of which are presented, was developed to compute the earth chord width measured by the ES and to predict the visibility times of the earth in the earth sensor field of view, as the spacecraft moves in T.O. in Roll-Sun-pointing orientation. A software, named the earth sensor scan characteristics prediction software (ESSCAN), was designed and developed incorporating the above mentioned method. The launch window over the year was generated for the spacecraft based on the mission requirement of the minimum duration of ES data for the calibration of the gyros. The earth chord width profiles were studied over the seasons and over the launch window duration. Another analysis was carried out on targeting for a higher inclination in Geosynchronous orbit and the deltav and propellant requirements were generated as a function of the launch date. For the first time in ISRO satellites, absolute sensor measurements were available for all three axes in apogee motor firing (AMF) orientation. The expected sensor readings in AMF orientations were studied from the viewpoint of verification of AMF attitude prior to the burn. KALPANA-1 was launched on September 12, 2002 by PSLV from SHAR in the designated launch window. The ES visibility predictions and earth chord width profiles generated by the ESSCAN software were used to plan the T.O. earth acquisition and gyro calibration operations. KALPANA-1 was positioned in its geostationary slot at 74 deg East after three AMF operations and three station acquisition maneuvers.

INTRODUCTION

KALPANA-1 is a geostationary meteorological spacecraft which carries a 3-channel very high resolution radiometer and a weather data relay transponder. It was the first s/c to be launched by ISRO's PSLV, from the Satish Dhawan Space Center, Sriharikota, into a geostationary transfer orbit with a perigee height of 252 km, synchronous apogee and 17.72 deg inclination. The s/c has a single solar panel on the south side which is automatically deployed soon after injection into GTO. The s/c positive pitch direction is designated as South since the pitch axis will be pointing southward in on-orbit orientation. KALPANA-1 is equipped with two Earth sensors (ES) which provide roll and pitch data. Each ES has two detectors, North and South, mounted at +/- 6.1 deg from yaw axis in the pitch-yaw plane. There is a digital sun sensor (DSS), mounted along the roll axis, which provides pitch and yaw information. There is the inertial reference unit (IRU) comprising three gyroscopes, mounted along each of the body axes. The liquid apogee motor (LAM) firing, to acquire the geosynchronous orbit, is carried out with the gyros as attitude reference. The gyros are calibrated prior to the LAM firing using the ES and DSS data.

The tasks assigned to us were

- To develop a method to compute the earth chord width measured by the ES as the s/c moves in GTO and to predict the periods of visibility of the Earth disc in the ES field of view (FOV)
- To generate the launch window for the s/c based mainly on the mission requirement of a minimum ES data duration of 45 min for the calibration of the gyros
- To generate the deltav and propellant requirements, as a function of the launch date, for targeting for a higher inclination in GSO
- To examine the expected ES and DSS readings in AMF orientation, as a function of the seasons and over the launch window, from the viewpoint of AMF attitude verification

EARTH CHORD WIDTH COMPUTATION

In the gyro calibration phase in GTO, the spacecraft's roll axis is oriented towards sun using the DSS. Then, earth is acquired in roll using the ES when the earth disc is fully visible in the ES FOV. With the DSS pitch and yaw and ES roll all reading zero, the s/c roll-yaw plane will be coincident with the spacecraft-sun-earth plane. The s/c body axes are defined as follows in the roll-sun-pointing orientation.

$$\hat{R} = \hat{s}$$

$$\hat{P} = (\hat{s} \times \hat{r}) / \left| \hat{s} \times \hat{r} \right|$$

$$\hat{Y} = \hat{R} \times \hat{P}$$

Where

$\hat{s}$: unit vector along s/c to sun direction

$\hat{r}$: unit radius vector

The roll-sun-pointing orientation is depicted in Fig. 1. In the s/c pitch-yaw plane, the north detector of the ES is mounted at 6.1 deg from yaw towards negative pitch. The south detector is mounted at the same angle towards positive pitch. The FOV of the detector scan is +/- 25 deg in the acquisition mode. The ES scan is across the pitch-yaw plane. The ES scan geometry is shown in Fig. 2.

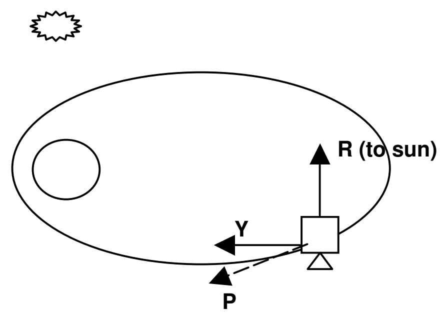


Fig. 1 S/c Orientation in T.O. for gyro-cal.

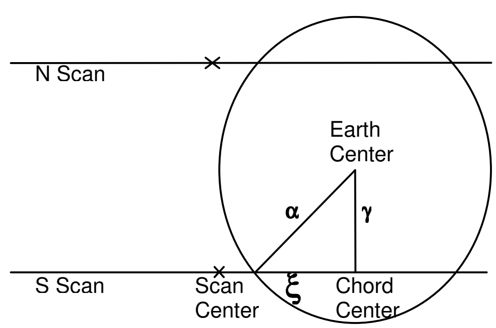


Fig. 2 Earth Sensor Scan Geometry

Using spherical trigonometry,

$$\cos\alpha = \cos\xi\cos\gamma + \sin\xi\sin\gamma\cos 90$$

$$\therefore \cos\xi = (\cos\alpha / \cos\gamma)$$

The maximum half chord width, α, which is half the angle subtended by the earth's disk at the s/c, is given by

$$\alpha = \sin^{-1}(R_e / r)$$

Where R_e is the earth's equatorial radius
r is the magnitude of the radius vector
ξ is the half chord width measured by the sensor and γ is the sensor mounting angle

The earth chord width measured by the ES, as the s/c moves in T.O. in roll-sun-pointing orientation, is computed using the above equation. The north and south scan widths will be equal. The chord width profile for the KALPANA-1 GTO is shown in Fig. 3. The actual earth visibility times for the ES are derived using the sensor FOV constraint. Let the angle between the scan center and the chord center be β. The scan center and the chord center directions for the South scan are constructed in the s/c body frame as follows:

South scan center direction $= [\cos\gamma \quad 0 \quad \sin\gamma]^T$
South chord center direction =
$[\cos\gamma\cos\alpha_r \quad \cos\gamma\sin\alpha_r \quad \sin\gamma]^T$

Where α_r is the right ascension of the earth direction unit vector in the body frame and γ is the sensor mounting. The earth disk visibility to the sensor starts when (β+ξ) is less than half the FOV and ends when (β+ξ) again becomes greater than half the FOV. The ES FOV taken is +/-22.5 deg with a margin of 10%.

LAUNCH WINDOW

The launch window of KALPANA-1 is determined by the following constraints specified by the mission

- A minimum of 45 min ES data duration is required for T.O. earth acquisition and gyro calibration activities
- Gyro calibration should be completed at least 75 min before apogee crossing to allow for preparation for and subsequent execution of AMF

A software was developed to compute the earth chord width measured by the ES in GTO in roll-sun-pointing orientation as described earlier and to generate the launch window open and close times for each day of the year. The main inputs for the software are the orbital parameters at injection (semimajor axis, eccentricity, inclination, argument of perigee, longitude of ascending node and mean anomaly), the ES FOV and visibility timeline constraints. The orbit is propagated from the injection time, using the two-body model, unto the end of the specified time interval in T.O., with a step size of 60 seconds. At every step, the chord width is calculated and the earth visibility start and end times in the ES FOV are derived based on the specified FOV constraint. The s/w then iterates over a specified time interval for the injection of the s/c into GTO and computes the launch window open and close times for the day based on the ES visibility timeline constraints specified by mission. The s/w further iterates for each day over the year and generates the launch window times over the year. The KALPANA-1 launch window, in terms of injection time, is shown in Fig. 4.

The launch window is generated with a sun-orbit geometry that leads to the ES visibility zone occurring in the apogee arc. This is advantageous for gyro calibration because the duration of valid ES data available will be more due to the s/c being slower in the apogee arc. After completion of the gyro drift rate estimation, the s/c control is transferred from ES and DSS to the IRU. The time interval between the transfer of control to IRU and the AMF burn start will be less which means that the gyro drift

Fig. 3 Earth Chord Width Profile for Kalpana-1 in G.T.O.
(ES FOV constraint not considered)

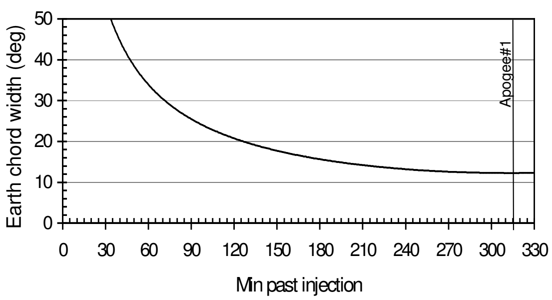
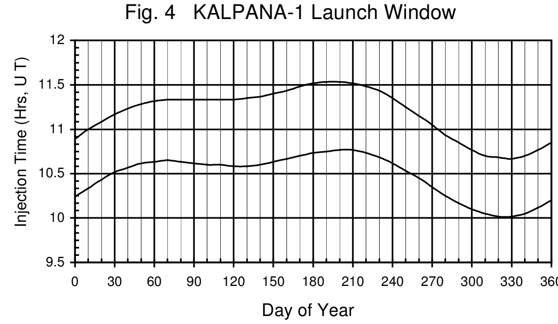


Fig. 4 KALPANA-1 Launch Window



period before burn start is reduced and hence the error in the burn due to the gyro drift rate estimation uncertainty will also be less. The angle between the ascending node and the sun vector projected onto the equatorial plane is provided for the various seasons in Table 1.

Table-1 : Sun Angle From Ascending Node For Different Seasons

Launch Date	Sun Angle From Asc. Node (deg) for	
	Launch Window open	Launch Window close
Mar 21	77.1	66.6
Jun 21	74.7	63.0
Sep 21	77.1	66.4
Dec 21	82.1	72.4

EARTH CHORD WIDTH PROFILES FOR VARIOUS LAUNCH DATES

The profile of the Earth chord width measured by the ES during the time the earth is in the ES FOV, the ES visibility period, was studied for the various seasons. The plot of the chord width during the ES visibility period, for launch window open case, for launch date of Mar 21, is shown in Fig. 5a. The ES visibility starts at 140 min past injection, which is nearly three hours before apogee, and exists unto 349 min past injection, which is 35 min past apogee. The chord width is about 18.6 deg at the visibility start and decreases, as the s/c moves towards apogee, to about 12.4 deg at visibility end. The effective ES data duration available for gyro calibration is 100 min, considering that calibration must be completed 75 min before apogee time to allow for AMF preparation. The altitude variation during the gyro calibration period was studied and the results were provided to the ES designers to decide on fixing the scale factor to be used for the ES roll data. The altitude

Fig. 5a Kalpana-1 Earth Chord Width Profile
Launch date : Mar 21, Window Open

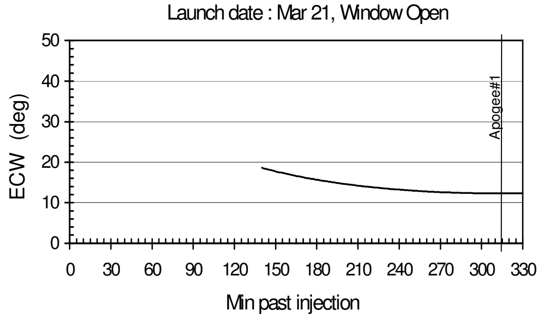
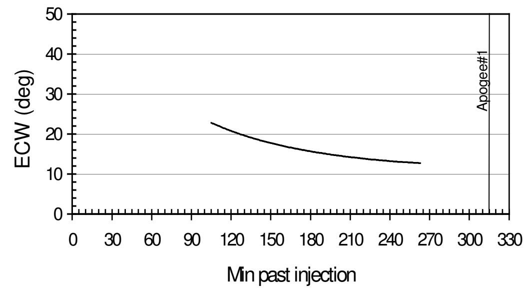


Fig. 5b Kalpana-1 Earth Chord Width Profile
Launch date : Mar 21, Window Close



at the ES visibility start time is over 26000 km. The ES designers stated that a scale factor of 1 could be used for the ES roll data, if the altitude is over 20000 km.

The plot of the Earth chord width during the ES visibility period for launch window close case, for launch date of Mar 21, is shown in Fig. 5b. The ES visibility starts at 105 min past injection and exists unto 263 min past injection, which is 51 min before apogee. The chord width is about 22.8 deg at the visibility start and gradually decreases to about 12.7 deg at visibility end. The altitude at the ES visibility start time is over 22000 km. The effective ES data duration available for gyro calibration is 135 min, considering that calibration must be completed 75 min before apogee time to allow for AMF preparation. The effective ES data duration available for gyro calibration operation increases from 100 min at window open to 135 min at window close, a plot of which is shown in Fig. 6.

The Earth chord width plots for the window open and close cases of Jun 21, Sep 21 and Dec 21 launch dates are presented in Fig. 7a, 7b, Fig. 8a, 8b and Fig.9a, 9b respectively. The chord width profiles are similar to the corresponding profiles for the Mar 21 launch case.

Fig. 6 Effective E S Visibility Duration For Gyro-Cal Over The Launch Window

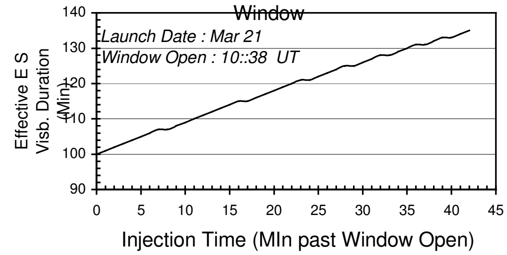


Fig. 7a. Kalpana-1 Earth Chord Width Profile
Launch date : Jun 21, Window Open

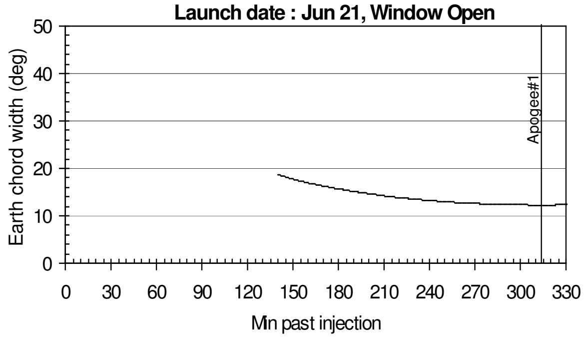


Fig. 7b. Kalpana-1 Earth Chord Width Profile
Launch date : Jun 21, Window Close

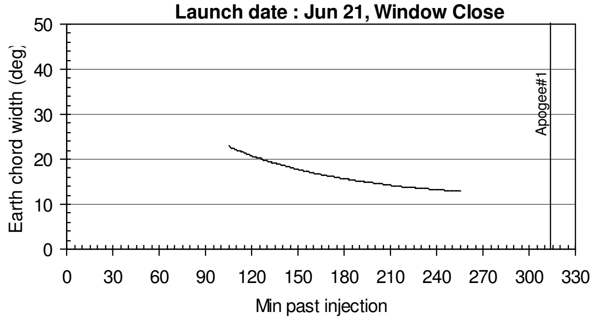


Fig. 8a. Kalpana-1 Earth Chord Width Profile
Launch date : Sep 21, Window Open

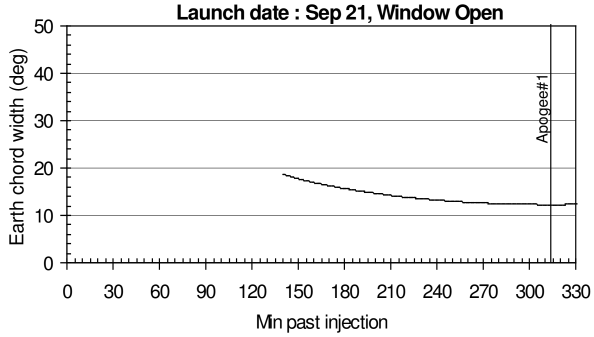


Fig. 8b. Kalpana-1 Earth Chord Width Profile
Launch date : Sep 21, Window Close

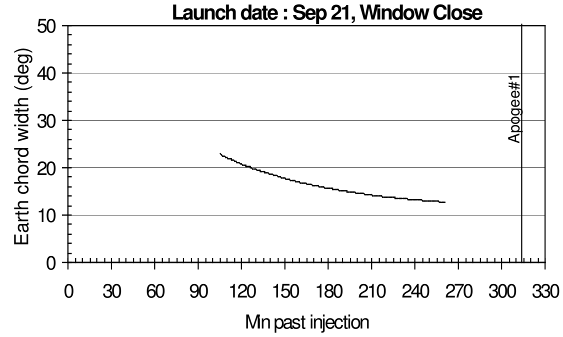


Fig. 9a. Kalpana-1 Earth Chord Width Profile
Launch date : Dec 21, Window Open

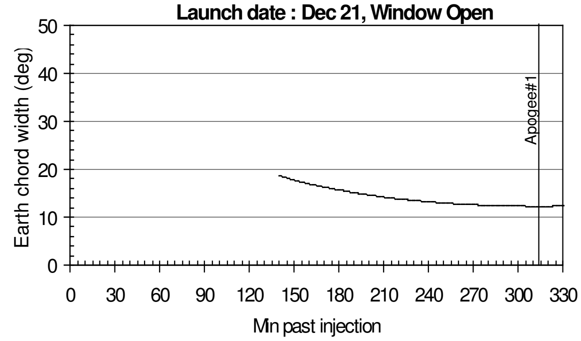
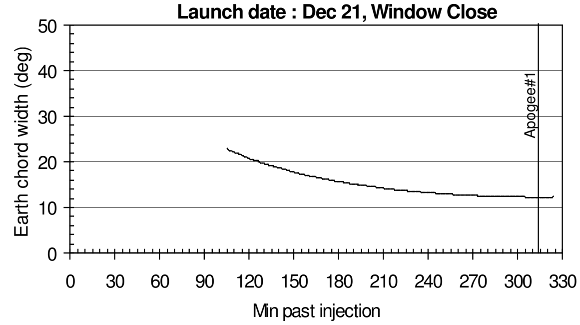


Fig. 9b. Kalpana-1 Earth Chord Width Profile
Launch date : Dec 21, Window Close



ECLIPSE DURATION

It was specified by the Mission that the eclipse duration in Transfer Orbit should not exceed 35 min. The eclipse duration in T.O. was computed for the launch window open and close cases of each of the four launch dates specified in Table-1. The eclipse duration was found to be within the specified limit. The maximum eclipse duration of about 32 min occurs for the launch window open time of Sep. 21 launch. The eclipse duration is minimum at about 20 min for Dec 21 launch.

HIGHER INCLINATION TARGETING IN GSO

Since KALPANA-1 is a meteorological satellite, the Mission needed a study on targeting for inclination higher than 0.1 deg in geosynchronous orbit. The AMF deltav and propellant requirements for targeting GSO inclination to 0.1, 0.5, 1.0 and 1.5 deg were computed, using the AMF strategy determination software (AMFS), for various launch dates over the year, considering the launch window mid time in each case. The strategy is to first achieve a higher inclination with optimal ascending node and start inclination control after it enters the control window of +/- 0.1 deg. The extension in the operational life of the s/c that can be obtained by following this plan is provided in Table-2.

Table-2 : Extension In Operational Life With Higher Inclination In GSO

Inclination at Beginning of Life (deg)	Operational Life Extension
0.5	5.5 months
1.0	1 year
1.5	1 yr. 7 mth

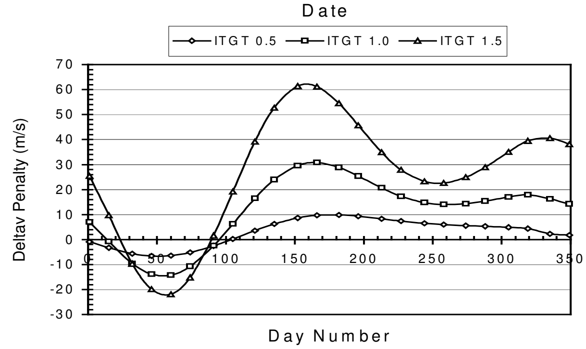
The plot of the AMF deltav penalties incurred in achieving the GSO with a higher inclination, as a function of the launch date, is provided in Fig. 10. The penalties are computed as the difference between the AMF deltav required for achieving the higher inclination in GSO and that required for achieving 0.1 deg inclination. The target ascending node is fixed at 270 deg for all cases. In Fig. 10, the negative values of deltav penalties actually indicate the gains in deltav. The region in Fig. 10 below the zero line, which shows the deltav gains, gives the favorable launch period for achieving higher inclination in GSO. This is the region where the T.O. ascending node is close to the desired target of 270 deg and hence, the node rotation required is less. The favorable launch periods for the different inclination targets are provided in Table-3.

Table-3 : Favorable Launch Periods for Achieving Higher Inclination In GSO

Inclination Target (deg)	Favorable Launch Period
0.5	Jan 1 to Apr 15
1.0	Jan 15 to Apr 1
1.5	Jan 22 to Apr 1

The maximum penalty in AMF deltav and propellant expenditure occurs if launch takes place in May-June period where the node rotation required is maximum. The maximum deltav penalty is about 10 m/s, 31 m/s and 61 m/s for 0.5 deg, 1 deg and 1.5 deg inclination targets respectively. The plot of the AMF propellant penalties incurred in achieving the GSO with a higher inclination, as a function of the launch date, is provided in Fig. 11. The maximum propellant penalty is about 2 kg, 6 kg and 12 kg for 0.5 deg, 1 deg and 1.5 deg inclination targets respectively. The on-orbit maintenance propellant requirement is, on an average, about 1 kg per month. Even though the AMF propellant penalty is maximum for a May-June launch, there is a net gain in the operational life of the s/c for the case of 0.5 deg inclination target. From Table-2, if we account for the above mentioned penalty in terms of operational life, the net life extension that we get, for the 0.5

Fig.10 AMF Deltav Penalty as a Function of Launch Date



deg inclination target, is 3.5 months.

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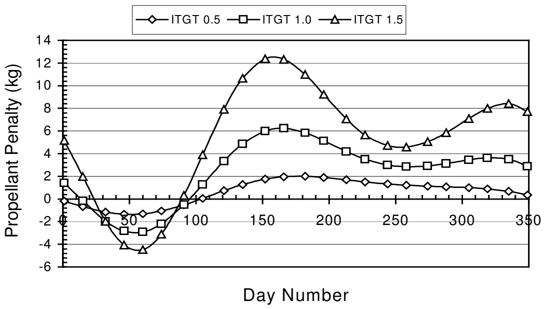
Fig.11 AMF Propellant Penalty as a Function of Launch Date



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EXPECTED SENSOR OUTPUTS IN AMF ORIENTATION

The LAM engine is mounted on the negative roll face of the s/c. The AMF orientation is shown in Fig. 12. The positive roll axis is the thrust axis and the yaw axis will point towards the earth. The field of view of the digital sun sensor, which is mounted along the roll axis, is +/- 32 deg. The linear range of the earth sensor in pitch is +/- 5.1 deg and that in roll is +/- 2.25 deg. During the Mission, after completion of the calibration of the gyros, the attitude control is transferred from the earth and sun sensors to the IRU. Then, about 45 min before the designated apogee motor firing start, the s/c is oriented to the desired AMF attitude from the Roll–sun-pointing attitude by means of an attitude maneuver carried out by the Attitude and Orbit Control subsystem. The s/c orientation for AMF is constructed in the AMF strategy determination software (AMFS) as follows

$$\hat{R} = \hat{u}$$
$$\hat{P} = (\hat{u} \times \hat{r}) / |\hat{u} \times \hat{r}|$$
$$\hat{Y} = \hat{R} \times \hat{P}$$

where

$\hat{u}$: *is the unit thrust direction*
$\hat{r}$: *is the unit radius vector*

For the first time in ISRO satellites, absolute sensor measurements are available for all three axes in AMF orientation. The expected ES and DSS readings in AMF orientation were computed in AMFS to provide to Mission a means of verification of the AMF orientation achieved. The s/c to sun unit vector is transformed from the Earth centered inertial frame to the s/c body frame defined above and the expected DSS pitch and yaw data are computed as follows:

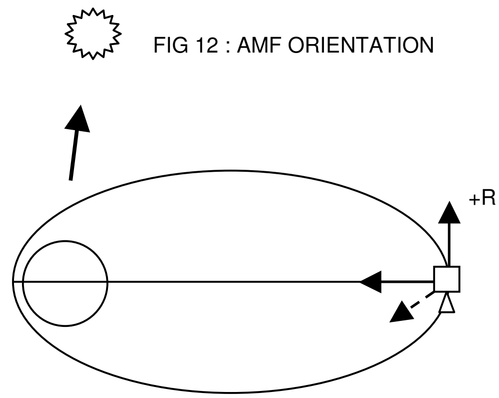


FIG 12 : AMF ORIENTATION

Expected DSS yaw $= -\tan^{-1}(\mathbf{s_b}(3)/\mathbf{s_b}(2))$
Expected DSS pitch $= \tan^{-1}(\mathbf{s_b}(1)/\mathbf{s_b}(2))$

Where $\mathbf{s_b}$ is the sun direction in the s/c body frame. The expected ES roll and pitch are computed as follows:

Expected ES roll $= \sin^{-1}(\mathbf{P} \cdot -\mathbf{r})$
Expected ES pitch $= \sin^{-1}(\mathbf{u} \cdot -\mathbf{r})$

Where **P** is the s/c pitch direction, **r** is the unit radius vector and **u** is the unit thrust direction (roll direction).

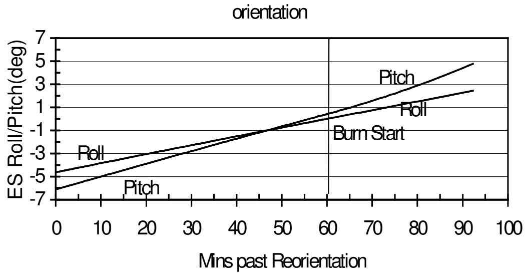
The nominal AMF strategy for KALPANA-1 is a three-burn strategy with the three burns to be carried out at apogees 2,4 and 6 respectively. It was decided to carry out the AMF operation with the thrust direction inertially held throughout the burn, using the gyros as attitude reference for all three axes. The nominal AMF strategy was generated and the expected sensor readings in the s/c orientation for AMF#1 were generated for four launch dates covering the seasons and for launch window open and close cases for each launch date. The expected DSS angles for the various cases are provided in Table-4. The DSS yaw ranges from –5.9 deg for Dec 21 launch to 43 deg for Jun 21 launch. The DSS pitch ranges from –5.9 deg for Dec 21 launch to nearly -29 deg for Jun 21 launch. This indicates that the sun will be outside the DSS FOV of 32 deg for launch dates around summer solstice. In the other seasons, the AMF orientation can be verified using the DSS readings.

The expected profiles of the ES roll and pitch in AMF orientation are shown in Fig. 13 for the launch at the window open on Sep 21. The ES pitch enters the linear range at about 50 min before burn start and the ES roll enters its linear range at about 29 min before burn start and both remain within the linear range till the burn end. The ES data profiles in AMF orientation were found to be similar over the launch window and over the seasons.

Table 4 : Sun angles in AMF#1 orientation

Injection Time (UT)	Launch window	Expected D S S	
		YAW (deg)	Pitch (deg)
Mar 21,10:38	Open	18.1	-10.8
Mar 21,11:20	Close	18.2	-21.8
Jun 21,10:42	Open	41.6	-14.7
Jun 21,11:29	Close	43.2	-28.8
Sep 21,10:24	Open	18.4	-11.2
Sep 21,11:07	Close	18.6	-22.5
Dec 21,10:09	Open	-5.9	-5.9
Dec 21,10:48	Close	-6.4	-14.9

Fig..13 Expected ES Roll & Pithch profile , AMF-1 orientation



CONCLUSION

A method was developed to compute the earth chord width measured by the earth sensor as the spacecraft moves in GTO, with the roll axis pointed towards sun, and to predict the periods of visibility of the earth disc in the sensor's field of view. A software was developed to generate the launch window for KALPANA-1 based mainly on the mission requirement of a minimum ES data duration of 45 min for the calibration of the gyros, which are used as attitude reference during the apogee motor firing operation. The eclipse duration in transfer orbit was studied for the various seasons. The deltav and propellant requirements, for targeting for a higher inclination in GSO, were worked out as a function of the launch date to assess the possible gains in the operational life of the s/c. The expected earth sensor and digital sun sensor readings in AMF orientation were studied, over the seasons and over the launch window, from the viewpoint of the AMF attitude verification before the start of the burn.

An operational software was developed for the prediction of earth sensor scan charecteristics (ESSCAN) using the earth chord width computation modules of the launch window generation software. KALPANA-1 was launched in the designated launch window on September 12, 2002 by the PSLV from the Satish Dhawan Space Centre, Sriharikota. The ES visibility predictions and earth chord width profiles generated by the ESSCAN software were used to plan the T.O. earth acquisition and gyro calibration operations. KALPANA-1 was positioned in its geostationary slot at 74 deg East after three AMF operations and three station acquisition maneuvers.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. N.K.Malik, Deputy Director, Controls and Mission Area, ISRO Satellite Center, for his constant support and encouragement. The authors thank Mr. T.K.Sundaramurthy, Mission Director, KALPANA-1, for assigning this work.

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